Army Research Laboratory

Strength of an Explosively-Formed Bond

by William S. de Rosset, Daniel J. Snoha, and Michael A. Minnicino

ARL-TR-3889 **September 2006**

NOTICES

Disclaimers

Army Research Laboratory
Aberdeen Proving Ground, MD 21005-5069

ARL-TR-3889 **September 2006**

Strength of an Explosively-Formed Bond

William S. de Rosset, Daniel J. Snoha, and Michael A. Minnicino
Weapons and Materials Research Directorate, ARL

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
September 2006

2. REPORT TYPE
Final

3. DATES COVERED (From - To)
January 2006–October 2006

4. TITLE AND SUBTITLE
Strength of an Explosively-Formed Bond

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
William S. de Rosset, Daniel J. Snoha, and Michael A. Minnicino

5d. PROJECT NUMBER
6162AH80

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Research Laboratory
ATTN: AMSRD-ARL-WM-MB
Aberdeen Proving Ground, MD 21005-5069

8. PERFORMING ORGANIZATION REPORT NUMBER
ARL-TR-3889

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Benet Laboratories
ATTN: AMSRD-AAR-AEW-T (B)
1 Buffington St.
Watervliet, NY 12189-4000

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
A test fixture used to determine the shear strength of an explosively-formed bond between a liner and gun tube is described. Tests were carried out in which the liner material yielded before the bond was broken. A finite-element analysis of the deformation indicated that the bond shear strength was in excess of 45 ksi. Internal stress measurements made by x-ray diffraction indicated the presence of residual hoop and radial stresses produced by the explosive bonding process. The hoop stresses at and near the bore were comparable to those achieved with the autofrettage process in a larger gun tube. The residual radial stress, along with frictional forces, may account for a large portion of the bond shear strength.

15. SUBJECT TERMS
gun tube liner, explosive bonding, internal stresses, autofrettage

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL	30	William S. de Rosset

19b. TELEPHONE NUMBER (*Include area code*)
410-306-0816

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

Contents

List of Figures

List of Tables

Acknowledgments

Special thanks go to Jonathan Montgomery, who helped with sample preparation for the x-ray diffraction work, as well as Paul Moy, who conducted the push-out tests. Thanks also go to Ryan Emerson, who made many helpful suggestions in the preparation of this report.

INTENTIONALLY LEFT BLANK.

1. Introduction

In January 2006, High Energy Metals, Inc. (HEMI) explosively bonded a Stellite 25 liner to a portion of a reamed-out M242 Bushmaster gun tube (*1*). This work followed previously successful attempts to explosively bond a refractory metal liner to the same type of gun tube by TPL, Inc. (*2*). Initial examination of the Stellite-lined tube revealed some portions of the liner-tube interface that did not have the characteristic wave pattern that typifies a strong bond. The extent of the nonwavy portion could not be discerned with a small number of microscopic examinations. Consequently, the overall quality of the bond was in doubt.

The need to perform a mechanical test to assess the bond shear strength between the gun tube and liner was recognized. A simple push-out test was decided upon as the most direct way to do this. In section 2, the sample preparation, fixturing, and the test procedure are presented. Section 3 presents the results of the measurements, along with a finite-element analysis that helps interpret the results.

High bond strength between a liner and gun tube is needed to keep the liner in place during firing. This is especially true for rifled barrels, where the reaction to the engraving forces tends to rotate the liner. In the past, mechanically pinning a refractory metal liner to an M242 gun tube was unsuccessful because the pins could not withstand the loads produced during the firing, resulting in liner movement (*3*). However, swaging a steel jacket over a Stellite rod can produce an acceptable bond in a 5.56-mm gun tube (*4*). It is reasonable to assume that there is a minimum bond strength required for acceptable performance of a given type of gun tube. While the exact figure is not known, the results of the present work indicate that the bond shear strength produced by explosive bonding is more than adequate for the M242 gun tube, even if there are small portions of the tube not perfectly bonded.

The internal stress generated as a result of the explosive bonding process may also contribute to the bond strength. In section 4, x-ray diffraction measurements of the internal stresses produced by explosive bonding will be presented and compared to internal stresses in other gun barrels that have either been autofrettaged or have had liners explosively bonded to them. Using a simple assumption about frictional forces, the contribution to the bond strength will be estimated and compared to those attainable with a shrink-fit process.

Section 5 contains a summary of the work.

2. Experimental Test Procedure

2.1 Sample Preparation

Three sections of an M242 barrel (labeled A, B, and C) were explosively clad with Stellite 25 by HEMI. The tubes were then sectioned, as shown in figure 1, to provide for various measurements (*1*). The dotted lines in this figure indicate additional cuts made at a later time to determine the inside diameter of the liner. Sections B3 and C3 were chosen as representative portions of the tubes. These parts were sawed into disc specimens, with one side being ground smooth. The final thickness of each disc was 0.25 in. This thickness was chosen so that the sample was thin enough to be tested (based on the load limit of the Instron machine) but thick enough to provide a representative bond surface area. Each saw cut and grinding operation accounted for approximately 0.2 in of material. Fifteen discs from each tube were produced and labeled B31–B46 for tube B and C31–C36 for tube C.

From previous work, it was found that the inside diameter of the liner varies with position along the tube axis. This was confirmed for sections B3 and C3. Measurements of the inside diameter are shown as a function of the distance from the leading (left) end of each tube in figure 2.

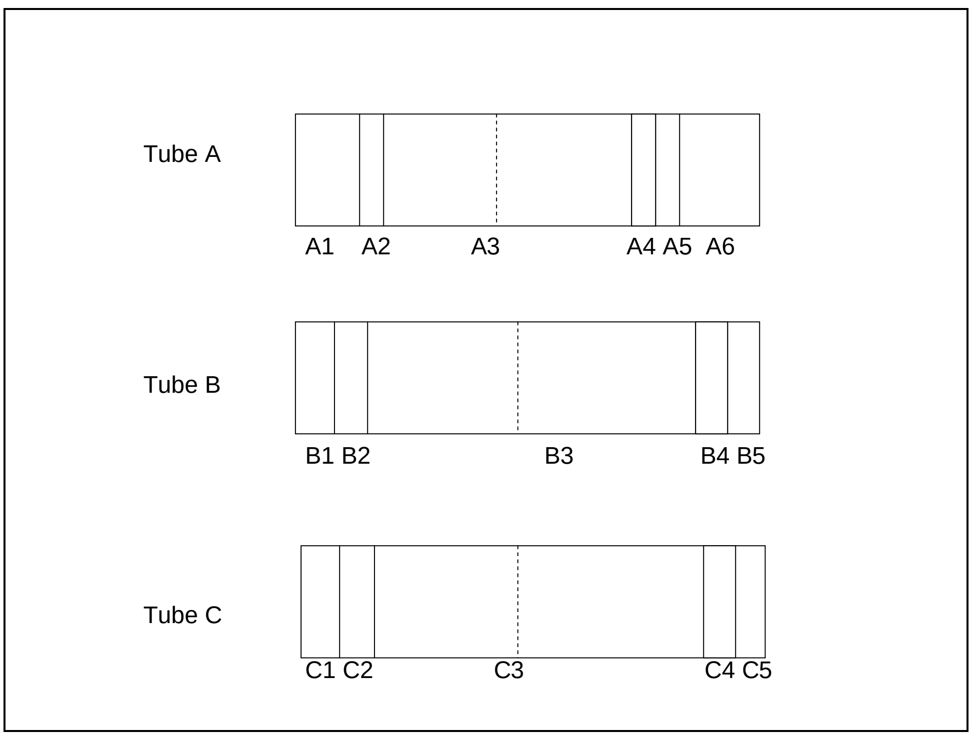

Figure 1. Labeling scheme for the sections saw cut from the gun tubes.

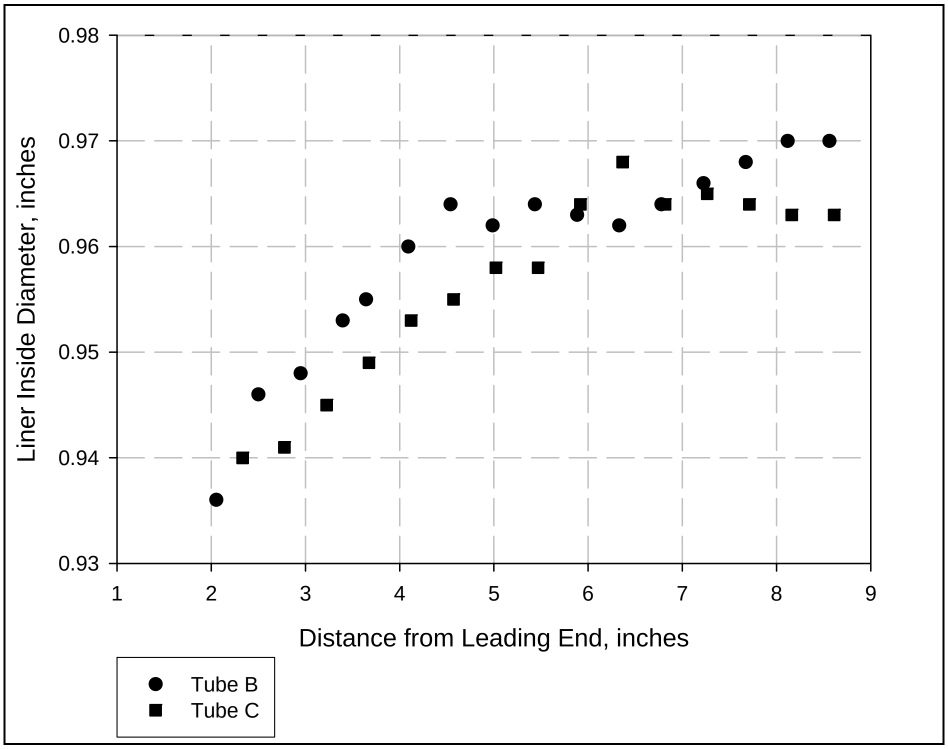

Figure 2. Liner inside diameter as a function of the distance from the leading end.

2.2 Test Fixture Description and Development

A cross-section illustration of the test fixture used for the push-out tests is shown in figure 3. It consisted of a pusher plug and a base plate. Samples were placed in the test fixture as shown, and an Instron machine was used to determine the load needed to extract the liner. The first pusher was made of stainless steel hardened to HRC 45. After one of the tests resulted in yielding of the pusher plug, the plug material was changed to Maraging 300 steel hardened to HRC 55. The base plate was made from 4340 steel hardened to HRC 31. A picture of the test fixture parts and a sample is shown in figure 4.

The dimensions of the test fixture that were adjusted as the tests progressed are shown as D1 and D2 in figure 3. These dimensions will depend on the actual size of the samples being tested. Since the inside diameter of the samples to be examined in these tests varied, the smallest liner inside diameter dictated the value of D2. In this instance, D2 was selected to be 0.93 in, which allowed the pusher to be used with all samples. Sample B31 (liner inner diameter of 0.936 in) was not used in this series of tests.

The value of D1 that was chosen to start the tests was 1.110 in. This value was based on the measurements of the liner-gun tube interface made in de Rosset (*1*). All of the measured gun tube inner diameter measurements exceeded 1.110 in for the sections of the barrels being examined (B3 and C3). The maximum value of the liner-gun tube interface diameter was measured to be 1.150 in. However, there was some uncertainty in this value, as well as the minimum value.

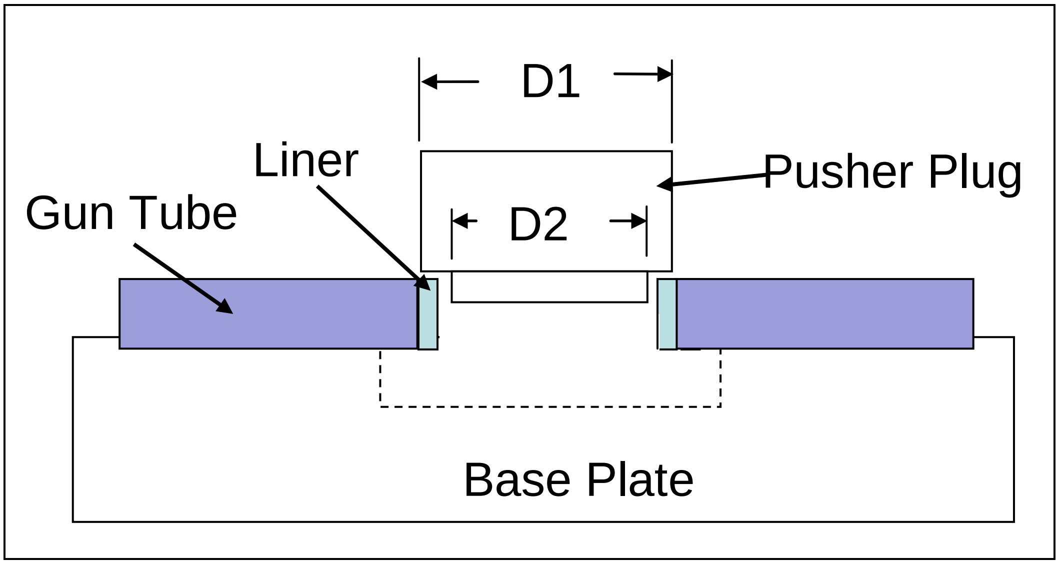

Figure 3. Cross-sectional view of the test fixture showing the placement of the sample to be tested.

Figure 4. Test fixture parts and sample C45.

The first test was conducted with sample C46. An Instron Model 1127 was used to apply a load to the test fixture and sample. The sample was loaded to 50×10^3 lb at a constant crosshead speed. No drop in the load was observed, indicating that the liner had not failed. The sample was removed from the Instron, at which time, a small amount of deformation in the liner was noticed. The test was continued using another load frame (MTS model 204-81) capable of applying a 100×10^3-lb load. The load was applied at a constant crosshead speed of 0.05 in/min. A load of 91.5×10^3 lb was achieved before the load began to decrease. The sample and test fixture were removed from the machine. However, the sample was stuck in the test fixture and had to be forcibly removed. After the parts were separated, it was noted that portions of the liner were still attached to the gun barrel. This was the first indication that the bond strength was higher than the shear strength of the liner.

The results of the test with C46 indicated that there might be some contact between the pusher plug and the gun barrel. Therefore, a paper shim between the liner and pusher plug was used for tests C45 and C44 to ensure a more accurate centering of the sample in the test fixture. Loads over 90×10^3 lb were also achieved for these tests. As before, the pusher and liner were stuck together as a result of the test.

The pusher plug outer diameter (D1) was reduced to 1.050 in to ensure that there was no interference between the pusher plug and gun tube. Tests with samples C43 and C42 resulted in a maximum load of over 60×10^3 lb. The load-displacement plots for these two tests are shown in figure 5.

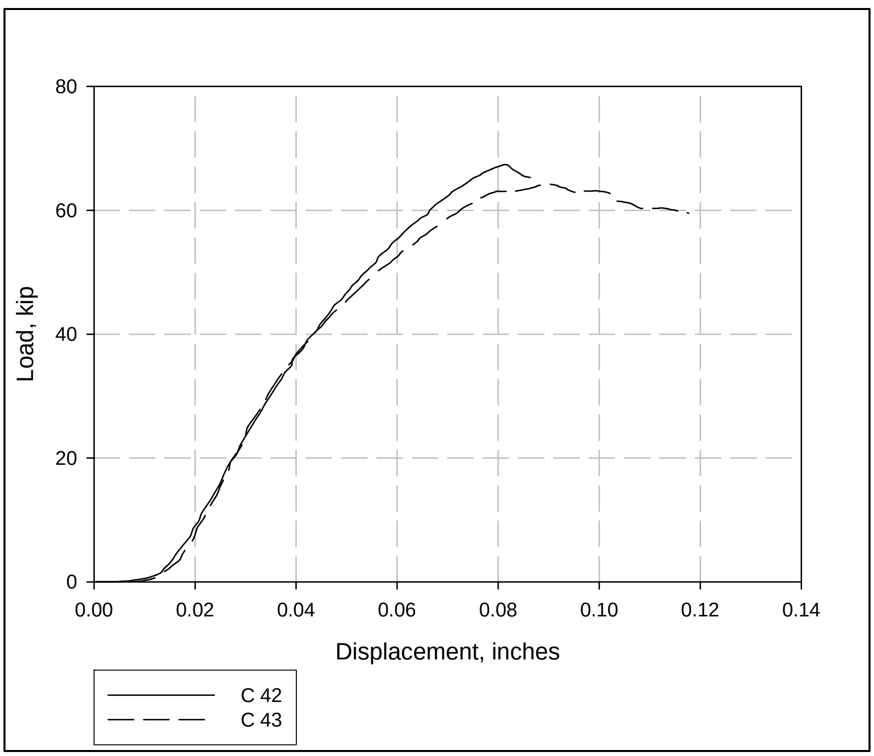

Figure 5. Load-displacement curves for tests C42 and C43.

The test with sample C41 continued until a load of 70×10^3 lb was achieved. The test was halted, and after removing the sample and test fixture from the load frame, it was observed that the pusher plug had sheared. A new plug made of Maraging 300 steel (HRC 55) was obtained and used to complete the tests. The final design of the test fixture is shown in the appendix.

Based on the analysis presented in section 3, the following standard test procedure was developed. A sample was placed in the test fixture, and a shim was applied to help center the pusher plug in the gun tube. The sample and fixture were then placed in the load frame, and the opening of the load frame was adjusted manually so that there was a very small gap between the platens and the sample/test fixture. The test was conducted in displacement-control mode (0.05 in/min) to a maximum displacement of 0.05 in, at which time, the test was concluded and the sample/test fixture removed from the test machine. The data from each test, taken at a sampling rate of one data point per second, were stored in an Excel* file.

3. Test Results and Interpretation

Table 1 shows the compressive loads on the sample at a crosshead displacement of 0.045 in into the sample. (Due to variation in the zero setting of the load frame, not all samples actually experienced a crosshead displacement of 0.05 in.) The mean values of the loads for tubes B and C are 46.4×10^3 lb and 49.8×10^3 lb, respectively. The standard deviations for these values are 1.7×10^3 lb and 3.5×10^3 lb for tubes B and C, respectively.

Table 1. Compressive loads at 0.045-in displacement.

Sample	**Load (10^3 lb)**	**Sample**	**Load (10^3 lb)**
B32	49.6	C31	53.7
B33	44.3	C32	54.6
B34	46.1	C33	56.9
B35	49.6	C34	50.9
B36	46.2	C35	49.4
B37	44.5	C36	50.6
B38	47.5	C37	45.6
B39	47.3	C38	45.2
B40	44.8	C39	47.8
B41	45.4	C40	47.8
B42	44.9	C42	47.0
B43	48.5	C43	47.9
B44	46.1	—	—
B45	45.6	—	—
B46	45.7	—	—

*Excel is a registered trademark of Microsoft Corporation.

The stress at the interface between the gun tube and liner will vary with the applied load and location on the interface. To help interpret the experimental results, a finite-element analysis was performed using ABAQUS. The finite-element model is shown in figure 6. The finite-element analysis utilized 6975 axisymmetric elements and frictionless contact between the steel pusher and the Stellite liner. The Stellite liner material is assumed to be elastic-perfectly plastic, with a yield of 895 MPa. The liner is assumed to be perfectly bonded to the gun tube, and failure of this interface is not allowed in the simulation. The assumption that the interface does not fail is consistent with the experimental observations. Prestress of the liner and the gun tube due to the bonding process is also neglected. The gun tube nodes along the bottom surface are constrained in the vertical direction. The simulated load is applied as a downward displacement of the nodes along the top surface of the steel pusher.

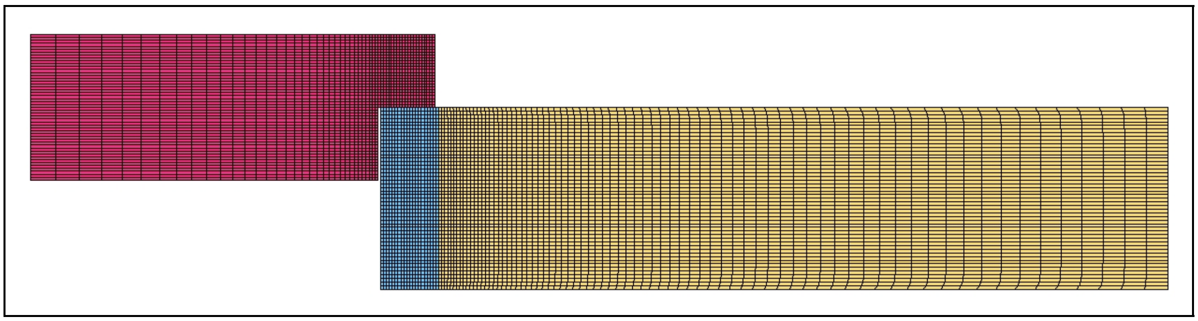

Figure 6. Axisymmetric finite-element model.

Figure 7 shows the simulated von Mises stress state at a steel pusher displacement of 0.0053 in (analysis step time is scaled by 1/10). Observation of figure 7 shows the classic 45° shear band indicating ductile yielding of the liner. Figure 7 also shows that the steel pusher confines the deformed Stellite liner material at the steel pusher's smaller diameter interface, leading to a stress concentration at this location. This plastic deformation of the liner is clearly the reason for the pusher plug becoming stuck in the sample.

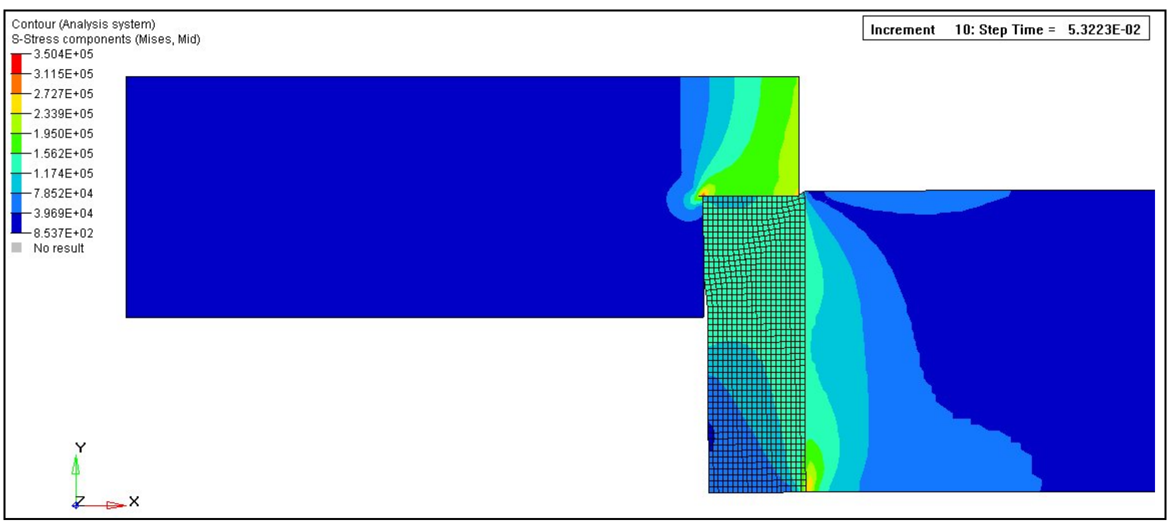

Figure 7. Von Mises stress state at 0.053 in of steel pusher vertical displacement.

The shear stress along the length of the liner-gun tube interface is plotted in figure 8. This stress is achieved for a displacement of 0.053 in of the pusher plug. The shear stress exceeds 65 ksi near the outer edges of the sample. At the center, it is above 45 ksi. This calculation provides evidence that the bond shear strength is greater than 45 ksi.

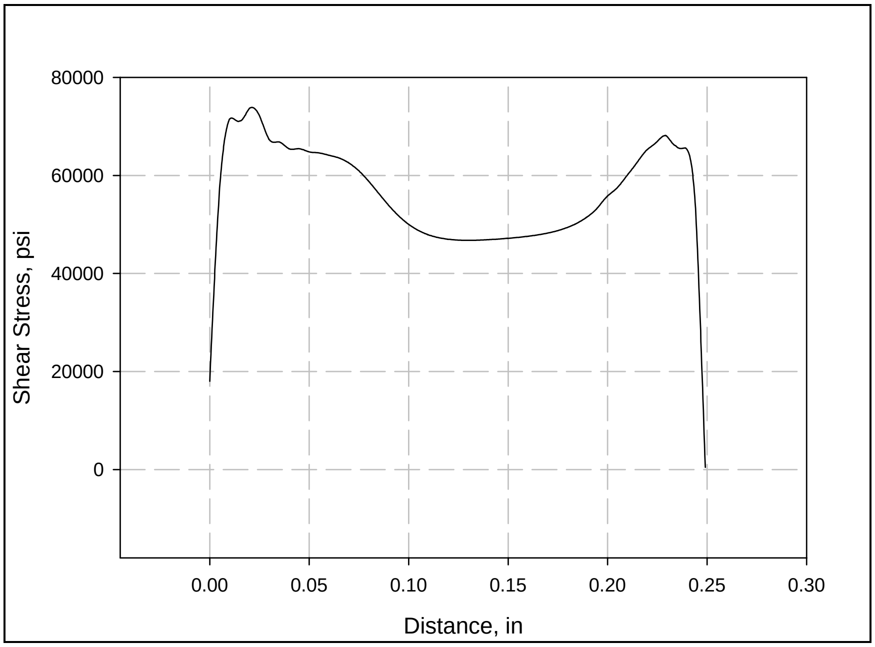

Figure 8. Shear stress as a function of position along liner-gun tube interface at 0.053-in pusher plug displacement.

However, the actual shear strength of the bond was not determined since the bond did not fail in any of the standard tests (table 1).

The finite-element analysis showed that the liner material yielded at very low displacement of the pusher plug (less than 0.002 in). This was also observed during testing. As a result, the tests were stopped when the crosshead displacement reading reached 0.050 in. Displacements greater than 0.050 in would simply have resulted in the pusher plug being more firmly attached to the liner.

4. Internal Stresses

4.1 Measured Internal Stresses

4.1.1 Experimental Procedure

A Technology for Energy Corp. (TEC) Model 1610 X-Ray Stress Analysis System, employing the $\sin^2\psi$ stress-measuring technique, was used to measure the residual stress (strain) produced in the steel gun tube from the explosive bonding process. All residual stress data were collected from a 4- or 10-positive ψ angle arrangement and CrKα radiation diffracted from the (211) lattice planes of the D6AC steel. (Residual stress measurements were not made on the steel gun tube prior to bonding.) The incident x-ray beam was collimated to provide a 2-mm diameter round irradiated area on the specimen surface. The x-ray elastic constant for D6AC steel, $(1 + \upsilon)/E$, required to calculate the macroscopic residual stress from the measured strain, was taken from published literature.

A 1/2-in thick disc specimen was sectioned from the leading end (specimen A2) and the trailing end (specimen A5) of gun tube A for residual stress analysis (see figure 1). After the specimens were saw cut from the gun tube, they were ground flat and parallel and chemically polished on one face. A polishing solution of 80% H_2O_2 (30% strength), 17.5% H_2O, and 2.5% HF (48% strength) was used to remove 0.010–0.015 in of material from the saw cut and ground surface, thereby exposing the explosive bonding induced internal stresses. Hoop and radial direction residual stresses were measured on the polished, cross-sectional surface along an inside diameter (ID) to outside diameter (OD) traverse in the arbitrarily chosen 0° and counter clockwise 90° orientations. The ID measurement location refers to the interface of the Stellite 25 liner and gun tube steel, and the OD measurement location was approximately 1.5 mm from the OD free surface. Measurements were performed at 0.05 in (1.27 mm) intervals from the ID to the 0.40-in (10.16-mm) location and then every 0.10 in (2.54 mm) for the remainder of the traverse. The precision of measurement for all data was ±2 ksi (±14 MPa). This value represented the average of the larger of either the counting statistics error or the probable error (goodness of fit of the d-spacing vs. $\sin^2\psi$ plots), both of which were generated for each measurement from statistical error analysis.

4.1.2 Results

The residual stress data in the D6AC steel acquired during this investigation are plotted in figures 9 and 10. The hoop direction residual stresses are very similar in magnitude and distribution at the 0° and 90° orientations for the leading and trailing end specimens (A2 and A5, respectively), with the maximum compressive stresses found at the ID location. This beneficial hoop stress becomes less compressive along the ID to OD traverse. At approximately 0.35 in. (8.89 mm) into the gun tube wall, the hoop stresses change from compressive to tensile and become increasingly tensile through the remaining wall thickness. The maximum tensile hoop stress was measured at the OD location.

The magnitude and distribution of the radial direction residual stresses are similar at the 0° and 90° specimen orientations but less symmetrical when comparing the leading and trailing ends of the gun tubes. Of particular note is that the radial stress changes from tensive to compressive at the 0.40-in (10.16-mm) measurement location on the trailing end specimen but not until the 0.60-in (15.24-mm) location on the leading end specimen. Additionally, the trailing end specimen radial

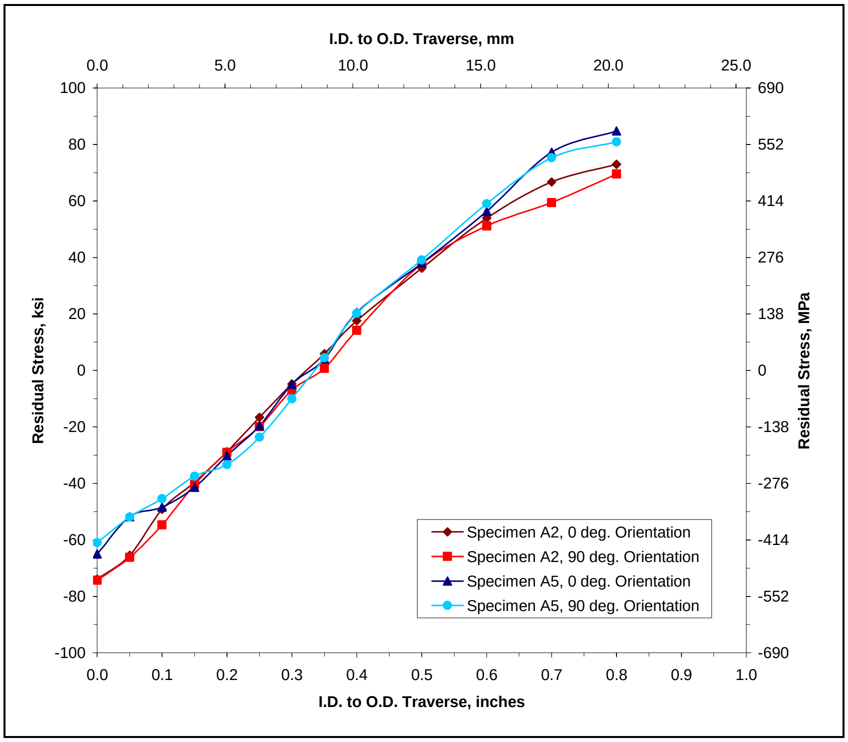

Figure 9. Hoop direction residual stress data from explosion bonded Stellite 25-lined Bushmaster gun tube specimens A2 (leading end) and A5 (trailing end).

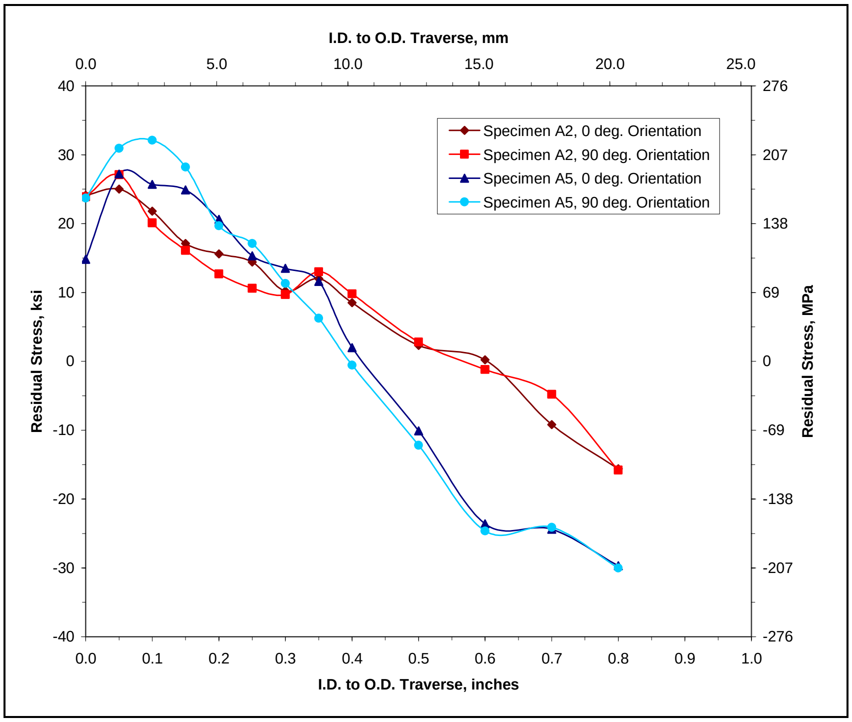

Figure 10. Radial direction residual stress data from explosion bonded Stellite 25-lined Bushmaster gun tube specimens A2 (leading end) and A5 (trailing end).

stress data had a greater negative trend along the traverse, with the average 0° and 90° orientation OD residual stress equal to –30 ksi (–207 MPa) vs. –16 ksi (–110 MPa) on the leading end specimen. Since there was no accounting for these anomalies with the specimen sectioning or chemical polishing procedures, the differences may be attributed to the explosive bonding setup or operation. Possible explanations are nonuniformity in the standoff distance between the liner and gun tube along the tube axis prior to bonding or asymmetrical explosive detonation rates, both of which also could have contributed to the inside diameter variation displayed in figure 10. However, inasmuch as the hoop direction residual stress data were in agreement at all measurement locations, it is likely that the reason(s) for the inconsistencies in the radial stresses cannot be precisely identified.

Of interest is the similarity in the hoop direction residual stress data for three different gun tubes. The data displayed in figure 11 came from measurements on an explosion-bonded Stellite 25-lined (at HEMI), a Ta-2.5W-lined Bushmaster gun tube (explosion-bonded at TPL, Inc.) (*5*), and a 120-mm extended length gun tube (swage-autofrettaged at Benet Laboratories) (*6*). The compressive stresses observed at the ID on the explosively-clad specimens, independent of the liner material and manufacturer, are approximately equivalent. Adjacent to the ID, the HEMI and TPL plots deviate somewhat. This result is probably due to one or more of the following: (1) different gun tube wall thickness (0.94 in and 1.22 in, respectively), (2) different liner thickness (see references 1 and 2), and (3) the manufacturer's particular explosive bonding parameters. As with the swage autofrettage process, the beneficial compressive hoop stresses produced from explosion bonding can be expected to increase the elastic strength of the gun tube and retard fatigue crack growth at the bore.

4.2 Bond Strength Contribution From Residual Stresses

The residual hoop stresses at the liner-gun tube interface are compressive, leading to a gripping action by the gun tube on the liner. In addition, an estimate of the bond strength contribution from the residual radial stress measurement can be made. First, assume that the explosive bond results in a smooth surface everywhere (i.e., no characteristic wavy pattern). Next, assume that the residual radial stress at the liner-gun tube interface is 25 ksi. (This was the value at three of the four measurement orientations shown in figure 10.) Assuming a coefficient of static friction between 0.3 and 1.0, the shear strength contribution due to the combination of radial stress and friction will be between 7.5 and 25 ksi.

It is interesting to compare this range of values with those that might be obtained with shrink-fitting a liner inside a gun tube. The shear strength of the bond will also result from the presence of a residual radial stress and friction. This process begins by machining the liner and gun tube so that the liner outer diameter is greater than the gun tube inner diameter. The gun tube is heated, and, at the same time, the liner is cooled. Thermal expansion and contraction effects then make it possible to slip the liner into the gun tube. When the temperature of the gun tube and

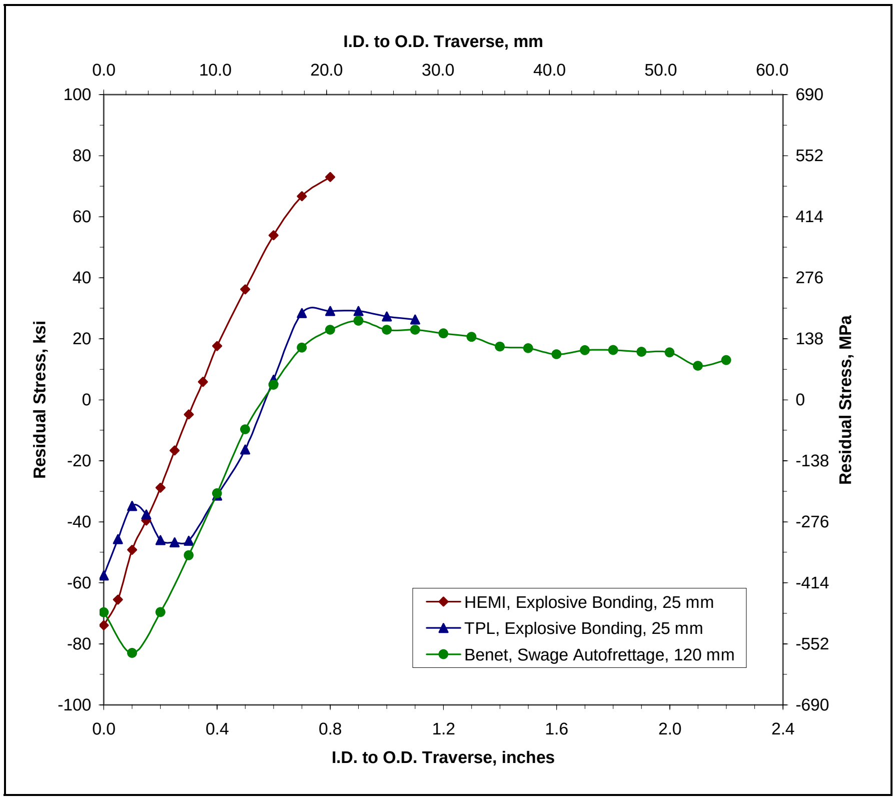

Figure 11. Hoop direction residual stress data from explosion bonded Stellite 25-lined and Ta-2.5W-lined Bushmaster gun tubes and swage autofrettaged 120-mm gun tube.

liner has reached equilibrium, internal stresses will develop that depend on the original amount of mismatch between diameters.

The temperature range over which the materials can be heated and cooled is bounded by practical considerations. For instance, the liner can be cooled using liquid nitrogen (–196 °C), and the steel can be heated up to about 350 °C to keep it below its first phase transformation temperature. Given that the coefficients of thermal expansion for the D6AC steel and Stellite 25 are 16.1 µm/m/°C and 12.9 µm/m/°C, respectively, a total mismatch of 205 µm can be obtained, assuming the initial diameters are 25.4 mm. (The mismatch is equivalent to approximately 8 mil.) The entire 205 µm cannot be used for the initial mismatch because some clearance will be needed to slide the liner into the gun tube. An optimistic assumption is that only 4 mil on the diameter will be needed for clearance. The allowable initial mismatch will then be 4 mil (102 µm).

Initially, the liner would have an inner diameter of 25.4 mm and an outer diameter of 30.48 mm. (A liner thickness of 0.1 in [2.54 mm] was used here.) The outer diameter of the gun tube is taken to be 76.2 mm (3.0 in). These dimensions can be used in the standard formula (see, for instance [*7*]) to approximate the internal radial stress, σ_r, generated in the gun tube as a result of the shrink-fit process:

$$\sigma_r = -(E\,\delta/b)\,(b^2 - a^2)(c^2 - b^2)/(2b^2(c^2 - a^2)), \tag{1}$$

where E is the modulus of the D6AC steel (210 MPa) and δ is 102 μm. In equation 1, a is the inner radius of the liner, b is the outer radius of the liner, and c is the outer radius of the gun tube. The resulting internal radial stress is compressive 203 MPa (29 ksi).

The stress necessary to initiate movement between the barrel and liner can be calculated using the same range of values for the coefficient of static friction that was used previously. This gives a possible range of 8.7–29 ksi values for the shear strength of the bond as a result of the shrink-fitting process. This range is seen to be comparable to that produced by the residual radial stress produced by explosive bonding.

5. Summary

A test fixture has been designed to determine the shear strength of an explosively-formed bond between an M242 medium-caliber gun tube and a Stellite 25 liner. Over 30 tests on two different sections of gun barrel were carried out. In each case, the liner yielded before the bond had the opportunity to fail. The shear strength of the bond could not be determined using the established test procedure because the bond never failed in these tests. However, a finite-element analysis indicated that the bond shear strength was likely to be greater than 45 ksi. Internal stresses were measured by x-ray diffraction. The measured stresses were used to estimate the contribution that a combination of residual radial stress and friction could make the bond shear strength. The range of values determined from this calculation, 7.5–25 ksi, was comparable to the range provided by a shrink-fit process.

6. References

1. de Rosset, W. S. *Explosive Bonding of Stellite* 25; ARL TR-3816; U.S. Army Research Laboratory: Aberdeen Proving Ground, MD, June 2006.

2. Lowey, R. F. *Gun Tube Liner Erosion and Wear Protection*; TPL-FR-ER31 (under contract DAAD19-99-C-0002); TPL, Inc.: Albuquerque, NM, 28 May 2002.

3. Bagnall, C.; Dalley, A. M.; Huston, J. F.; Martin, N. R.; McMullen, P. J.; Miller, C. S.; Papesch, C. A.; Sinosky, J. T. III; Valencia, J. J.; Guillard, S. *Advanced Gun Barrel Technology Initiative, Final Report: Modeling, Metallurgy and Firing Test Report for the M242 Mo-ODS Partially Lined Barrel*; TR no. 98–25; National Center for Excellence in Metalworking Technology: Johnstown, PA, 2 July 1998.

4. Livermore, G.; Sadowski, L. *Barrel Weight Reduction*; ARAEW-TR-05005; U.S. Army Armament Research, Development and Engineering Center: Picatinny, NJ, May 2005.

5. Pepi, M.; Snoha, D. J.; Montgomery, J. S.; de Rosset, W. S. *Examination of Intermetallic Phases and Residual Stresses Resulting from Explosive Bonding of Refratory Metal Gun Tube Liners*; ARL-MR-550; U.S. Army Research Laboratory: Aberdeen Proving Ground, MD, February 2003.

6. Snoha, D. J. Letter report to Benet Laboratories, Watervliet, NY, January 1993.

7. Timoshenko, S. *Strength of Materials, Part II, Advanced Theory and Problems*; 14th printing; D. Van Nostrand Company: New York, NY, June 1953.

Appendix. Test Fixture Design

The final design recommended for the push-out tests is shown in figure A-1. Note that the dimensions of the pusher plug have to be modified for the particular values of the inner diameters for the liner and gun tube.

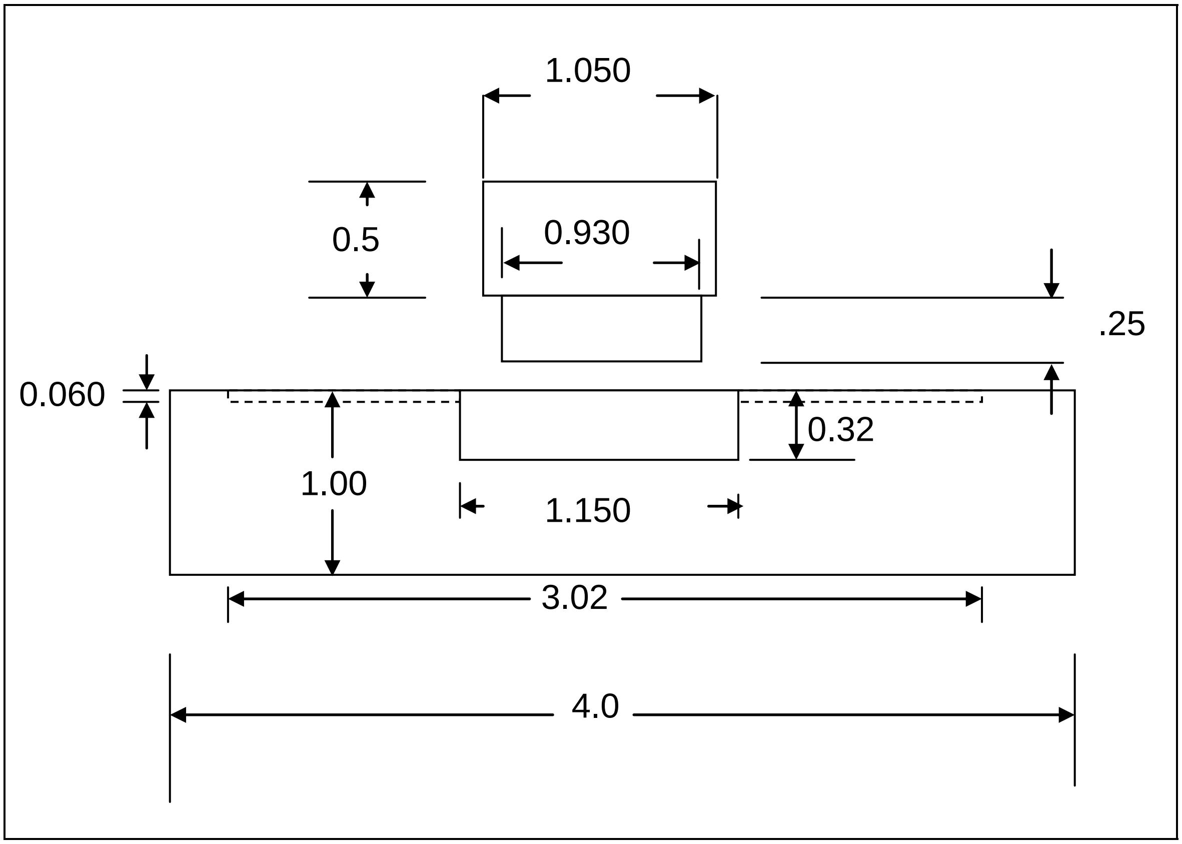

Figure A-1. Final test fixture configuration; all dimensions in inches.

NO. OF COPIES	ORGANIZATION
1 (PDF ONLY)	DEFENSE TECHNICAL INFORMATION CTR DTIC OCA 8725 JOHN J KINGMAN RD STE 0944 FORT BELVOIR VA 22060-6218
1	US ARMY RSRCH DEV & ENGRG CMD SYSTEMS OF SYSTEMS INTEGRATION AMSRD SS T 6000 6TH ST STE 100 FORT BELVOIR VA 22060-5608
1	DIRECTOR US ARMY RESEARCH LAB IMNE ALC IMS 2800 POWDER MILL RD ADELPHI MD 20783-1197
3	DIRECTOR US ARMY RESEARCH LAB AMSRD ARL CI OK TL 2800 POWDER MILL RD ADELPHI MD 20783-1197

ABERDEEN PROVING GROUND

1	DIR USARL AMSRD ARL CI OK TP (BLDG 4600)

NO. OF COPIES	ORGANIZATION
1	DIRECTOR USARL AMSRD ARL SE DE R ATKINSON 2800 POWDER MILL RD ADELPHI MD 20783-1197
5	DIRECTOR USARL AMSRD ARL WM MB A ABRAHAMIAN M BERMAN M CHOWDHURY T LI E SZYMANSKI 2800 POWDER MILL RD ADELPHI MD 20783-1197
1	COMMANDER US ARMY MATERIEL CMD AMXMI INT 9301 CHAPEK RD FORT BELVOIR VA 22060-5527
2	PM MAS SFAE AMO MAS MC PICATINNY ARSENAL NJ 07806-5000
1	US ARMY ARDEC AMSTA AR TD PICATINNY ARSENAL NJ 07806-5000
1	US ARMY ARDEC AMSRD AAR AEM D J LUTZ BLDG 354 PICATINNY ARSENAL NJ 07806-5000
1	DEPARTMENT OF THE ARMY RDECOM ARDEC AMSRD AAR EMO F PICATINNY ARSENAL NJ 07806-5000

NO. OF COPIES	ORGANIZATION
6	US ARMY ARDEC AMSTA AR CCH A F ALTAMURA D VO R HOWELL A VELLA M YOUNG L MANOLE PICATINNY ARSENAL NJ 07806-5000
1	US ARMY ARDEC AMSRD AAR AEM T M NICOLICH BLDG 65 SOUTH PICATINNY ARSENAL NJ 07806-5000
1	US ARMY ARDEC AMSRD AAR AEM M LUCIANO M PALATHINGUL BLDG 65 SOUTH PICATINNY ARSENAL NJ 07806-5000
1	US ARMY ARDEC AMSRD AAR AEM S MUSALLI BLDG 65 SOUTH PICATINNY ARSENAL NJ 07806-5000
1	US ARMY ARDEC AMSRD AAR EMB R CARR BLDG 1 PICATINNY ARSENAL NJ 07806-5000
1	US ARMY ARDEC SFAE AMO MAS SETI T C LIVECCHIA BLDG 354 SOUTH PICATINNY ARSENAL NJ 07806-5000

NO. OF COPIES	ORGANIZATION
1	US ARMY ARDEC SFAE AMO MAS LC D RIGOGLIOSO BLDG 354 M829E3 IPT PICATINNY ARSENAL NJ 07806-5000
1	RDECOM ARDEC AMSRD AAR EMO F BLDG 1 PICATINNY ARSENAL NJ 07806-5000
1	PM MAS SFAE AMO MAS PICATINNY ARSENAL NJ 07806-5000
1	PM MAS SFAE AMO MAS CHIEF ENGINEER PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER US ARMY TACOM AMSTA SF WARREN MI 48397-5000
1	COMMANDER US ARMY TACOM PM COMBAT SYSTEMS SFAE GCS CS 6501 ELEVEN MILE RD WARREN MI 48397-5000
1	DIRECTOR AIR FORCE RESEARCH LAB MLLMD D MIRACLE 2230 TENTH ST WRIGHT PATTERSON AFB OH 45433-7817
1	OFC OF NAVAL RESEARCH J CHRISTODOULOU ONR CODE 332 800 N QUINCY ST ARLINGTON VA 22217-5600

NO. OF COPIES	ORGANIZATION
1	COMMANDER US ARMY TACOM PM SURVIVABLE SYSTEMS SFAE GCSS W GSI H M RYZYI 6501 ELEVEN MILE RD WARREN MI 48397-5000
1	COMMANDER WATERVLIET ARSENAL SMCWV QAE Q B VANINA BLDG 44 WATERVLIET NY 12189-4050
2	SFSJM CDL HQ US ARMY JNT MUNITIONS CMND AMSIO SMT R CRAWFORD W HARRIS 1 ROCK ISLAND ARSENAL ROCK ISLAND IL 61299-6000
1	NSWC DAHLGREN DIV CODE G06 DAHLGREN VA 22448
1	US ARMY TARDEC AMSRD TAR R D TEMPLETON 6501 E 11 MILE RD MS 263 WARREN MI 48397-5000
2	USA SBCCOM MATERIAL SCIENCE TEAM AMSSB RSS J HERBERT M SENNETT KANSAS ST NATICK MA 01760-5057
1	USA SBCCOM PM SOLDIER SPT AMSSB PM RSS A J CONNORS KANSAS ST NATICK MA 01760-5057

NO. OF COPIES	ORGANIZATION
14	BENET LABS AMSTA AR CCB R FISCELLA M SOJA E KATHE M SCAVULO G SPENCER P WHEELER S KRUPSKI J VASILAKIS G FRIAR R HASENBEIN AMSTA CCB R S SOPOK E HYLAND D CRAYON R DILLON WATERVLIET NY 12189-4050
1	NSWC TECH LIBRARY CODE B60 17320 DAHLGREN RD DAHLGREN VA 22448
2	COMMANDER NSWC CARDEROCK DIVISION R PETERSON CODE 2020 M CRITCHFIELD CODE 1730 BETHESDA MD 20084
7	DIRECTOR US ARMY NGIC D LEITER MS 404 M HOLTUS MS 301 M WOLFE MS 307 S MINGLEDORF MS 504 J GASTON MS 301 W GSTATTENBAUER MS 304 J CRIDER MS 306 2055 BOULDERS RD CHARLOTTESVILLE VA 22911-8318
1	AFRL MLBC 2941 P ST RM 136 WRIGHT PATTERSON AFB OH 45433-7750

NO. OF COPIES	ORGANIZATION
7	US ARMY RESEARCH OFC A CROWSON H EVERITT J PRATER G ANDERSON D STEPP D KISEROW D SKATRUD PO BOX 12211 RESEARCH TRIANGLE PARK NC 27709-2211
7	US ARMY SBCCOM SOLDIER SYSTEMS CENTER BALLISTICS TEAM J WARD W ZUKAS P CUNNIFF J SONG MARINE CORPS TEAM J MACKIEWICZ AMSSB RCP SS W NYKVIST S BEAUDOIN KANSAS ST NATICK MA 01760-5019
1	DIRECTOR LLNL M FINGER L-020 PO BOX 808 LIVERMORE CA 94550
1	OSD JOINT CCD TEST FORCE OSD JCCD R WILLIAMS 3909 HALLS FERRY RD VICKSBURG MS 29180-6199
2	DARPA S WAX L CHRISTODOULOU 3701 N FAIRFAX DR ARLINGTON VA 22203-1714
1	HYDROGEOLOGIC INC SERDP ESTCP SPT OFC S WALSH 1155 HERNDON PKWY STE 900 HERNDON VA 20170

NO. OF COPIES	ORGANIZATION
3	NASA LANGLEY RESEARCH CTR AMSRD ARL VT W ELBER MS 266 F BARTLETT JR MS 266 G FARLEY MS 266 HAMPTON VA 23681-0001
1	DIRECTOR DEFENSE INTLLGNC AGNCY TA 5 K CRELLING WASHINGTON DC 20310
1	ALLIANT TECHSYSTEMS INC 4700 NATHAN LN N PLYMOUTH MN 55442-2512
1	PROJECTILE TECHNOLOGY INC 515 GILES ST HAVRE DE GRACE MD 21078
2	GENERAL DYNAMICS OTS FLINCHBAUGH DIV K LINDE T LYNCH PO BOX 127 RED LION PA 17356
2	UDLP G THOMAS M MACLEAN PO BOX 58123 SANTA CLARA CA 95052
2	UDLP R BRYNSVOLD P JANKE MS 170 4800 E RIVER RD MINNEAPOLIS MN 55421-1498
1	GDLS DIVISION D BARTLE PO BOX 1901 WARREN MI 48090
1	GENERAL DYNAMICS AMPHIBIOUS SYS SURVIVABILITY LEAD G WALKER 991 ANNAPOLIS WAY WOODBRIDGE VA 22191

NO. OF COPIES	ORGANIZATION
5	INST FOR ADVANCED TECH H FAIR I MCNAB P SULLIVAN S BLESS C PERSAD 3925 W BRAKER LN AUSTIN TX 78759-5316
1	R EICHELBERGER CONSULTANT 409 W CATHERINE ST BEL AIR MD 21014-3613
1	SAIC G CHRYSSOMALLIS 8500 NORMANDALE LAKE BLVD SUITE 1610 BLOOMINGTON MN 55437-3828
1	SOUTHWEST RESEARCH INST ENGR & MATL SCIENCES DIV J RIEGEL 6220 CULEBRA RD PO DRAWER 28510 SAN ANTONIO TX 78228-0510
3	DIRECTOR USARL AMSRD ARL WM MB A FRYDMAN 2800 POWDER MILL RD ADELPHI MD 20783-1197
1	DEPARTMENT HEAD US MILITARY ACADEMY K NYGREN CIVIL & MECH ENGRG DEPT WEST POINT NY 10996-1792
1	US ARMY ARDEC AMSRD AAR ATD B MACHAK BLDG 1 PICATINNY ARSENAL NJ 07806-5000
1	US ARMY ARDEC AMSRD AAR AEW A(D) M CHIEFA BLDG 1 PICATINNY ARSENAL NJ 07806-5000

NO. OF COPIES	ORGANIZATION
1	US ARMY ARDEC AMSTA AR FSP G M SCHIKSNIS BLDG 1 PICATINNY ARSENAL NJ 07806-5000
1	US ARMY ARDEC AMSTA AR FSP G D CARLUCCI BLDG 1 PICATINNY ARSENAL NJ 07806-5000

ABERDEEN PROVING GROUND

NO. OF COPIES	ORGANIZATION
1	US ARMY ATC CSTE DTC AT AD I W C FRAZER 400 COLLERAN RD APG MD 21005-5059
78	DIR USARL AMSRD ARL CI AMSRD ARL O AP EG M ADAMSON AMSRD ARL SL BM D BELY AMSRD ARL WM J SMITH AMSRD ARL WM B CHIEF T KOGLER AMSRD ARL WM BA D LYON AMSRD ARL WM BC J NEWILL P PLOSTINS AMSRD ARL WM BD P CONROY B FORCH M LEADORE C LEVERITT R LIEB R PESCE-RODRIGUEZ A ZIELINSKI AMSRD ARL WM BF S WILKERSON AMSRD ARL WM M J MCCAULEY S MCKNIGHT AMSRD ARL WM MA CHIEF L GHIORSE E WETZEL AMSRD ARL WM MB J BENDER T BOGETTI J BROWN L BURTON R CARTER K CHO W DE ROSSET G DEWING R DOWDING W DRYSDALE R EMERSON D GRAY D HOPKINS R KASTE L KECSKES M MINNICINO B POWERS D SNOHA J SOUTH M STAKER J SWAB J TZENG AMSRD ARL WM MC CHIEF R BOSSOLI E CHIN D GRANVILLE J LASALVIA J MONTGOMERY F PIERCE E RIGAS W SPURGEON AMSRD ARL WM MD B CHEESEMAN P DEHMER R DOOLEY G GAZONAS S GHIORSE M KLUSEWITZ J SANDS D SPAGNUOLO S WALSH S WOLF

NO. OF COPIES	ORGANIZATION
	AMSRD ARL WM TA M BURKINS B GOOCH T HAVEL C HOPPEL E HORWATH J RUNYEON M ZOLTOSKI AMSRD ARL WM TB P BAKER AMSRD ARL WM TC R COATES AMSRD ARL WM TD D DANDEKAR M RAFTENBERG S SCHOENFELD T WEERASOORIYA AMSRD ARL WM TE CHIEF J POWELL